Accurate and Efficient Frequency Evaluation of a Ring Oscillator

Application Note 4070-3

Agilent 4070 Series of Semiconductor Parametric Testers

Introduction

With the continued demand for higher-speed operation of semiconductor devices, the measurement of gate delay and interconnect delay has become more important than ever. These two parameters play key roles in determining the ultimate speed of device operation. High-speed operation has always been critical for successful logic devices. With new market pressures on peripheral devices, the need for high-speed operation is now becoming necessary for memory devices.

It is commonly known that gate delay time can be evaluated by measuring the oscillation frequency of a ring oscillator test structure.

Interconnect delay, which is becoming significant for devices designed with less than 0.8 µm gate length, can also be evaluated using a specially designed ring oscillator test structure.

Because of this, measurement of the oscillation frequency of a ring oscillator has become an indispensable tool for semiconductor device engineers when designing high-speed devices.

This measurement can also be used to determine if devices are fabricated as designed, or to model AC characteristics by supplying measured data to simulation software. Today, measurement of the frequency of the ring oscillator is feasible on the production line. This application note introduces a precise and fast measurement method to measure the oscillation frequency of a ring oscillator structure using a spectrum analyzer integrated into the Agilent 4072A Advanced Parametric Tester.

Conventional Testing Methods

The objective of measuring the ring oscillator's frequency is to obtain the gate delay time. This can be calculated from the following equation:

$$t_{pLH} + t_{pHL} = \frac{1}{(2n+1)^{*}\ freq}$$

freq: Oscillation frequency

2n+1: Number of stages (or inverters)

t_{pLH}: Gate delay time for the output to change from low to high

t_{pHL}: Gate delay time for the output to change from high to low

If a test structure consisting of a ring oscillator and long interconnect line is used, the interconnect delay can also be evaluated by comparing the result with another test structure that consists of only a ring oscillator. Often a bench-top frequency counter or oscilloscope connected to a manual probe station is used to measure the oscillation frequency of a ring oscillator. The frequency counter solution has the advantage of lower cost and higher measurement speed. However, there are some disadvantages.

- The frequency counter cannot detect waveform distortion caused by the device itself or by the measurement test system, so the measured result can be less reliable.
- It may pick up harmonics.
- If there is an offset voltage present, the frequency counter cannot accurately measure zero crossings.

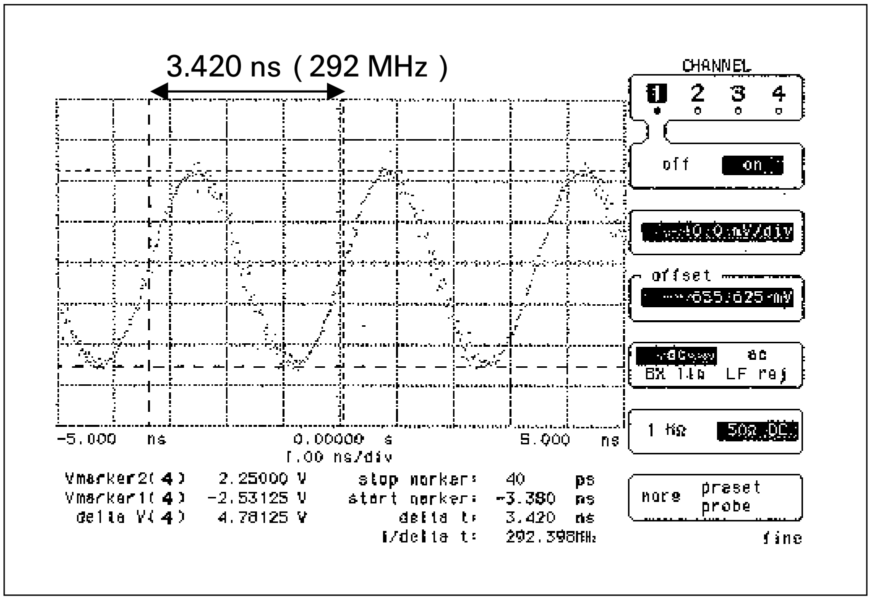

Figure 1. Waveform of a ring oscillator through the switching matrix of the Agilent 4072A Parametric Tester

The oscilloscope solution is reliable because the actual waveform can be monitored. However, there are also some disadvantages with this method.

- The measurement and analysis speed is slow.
- In a fully automated measurement system, it may return an incorrect frequency due to waveform distortion.
- The cost is high.

The oscilloscope solution is good for a measurement when using a manual probe station because the signal loss or distortion caused by the measurement path is small. However, if integrated into an automatic test system that includes a switching matrix, an oscilloscope is no longer a suitable solution due to the waveform distortion at higher frequencies.

If a parametric tester, integrated with a frequency counter or an oscilloscope, is used for the evaluation, the design of the test structure has to be considered as well. To minimize the waveform distortion caused by the switching matrix, the oscillation frequency needs to be reduced. Therefore, the area of the test structure can become very large due to the increased number of stages required to reduce the frequency of oscillation. For example, to reduce the oscillation frequency from 100 MHz to 10 MHz, the area of the ring oscillator increases by about ten times, using up precious space on a wafer.

Solution Using the Agilent 4072A and a Spectrum Analyzer

The 4072A Advanced Parametric Tester reduces one of the bottlenecks that prevent a semiconductor parametric tester from being used for this application.

The HF (High Frequency) port of the 4072A has outstanding high frequency characteristics.

An oscilloscope output of an actual ring oscillator output waveform monitored through the switching matrix of the 4072A is shown in Figure 1. The successful monitoring of an oscillation frequency that is close to 300 MHz is displayed.

Utilizing the superior frequency characteristics of the 4072A will reduce many of the difficulties of ring oscillator evaluation.

A spectrum analyzer can be integrated in the 4072A and used to measure the frequency of the ring oscillator. A spectrum analyzer with a reasonably wide frequency range, such as 1.5 GHz, is recommended. The spectrum analyzer is used in the system to directly measure the highest amplitude frequency, which should correspond to the oscillation frequency of the ring oscillator. There are several benefits that make a spectrum analyzer suitable for this application.

- Measurement speed is fast.
- The oscillation frequency can be precisely measured in the presence of an offset voltage.
- The usable frequency range is higher due to the wide baseband frequency range of the spectrum analyzer.
- The cost is reasonable.

Most Agilent spectrum analyzers have marker peak detection functions and GPIB control capability. These are both essential for configuring an automated measurement system.

Figure 2 shows an example measurement program using the TIS (Test Instruction Set) commands of the parametric tester and a custom driver for a spectrum analyzer.

Italic : Spectrum analyzer control
Bold : Agilent 4072A's TIS command

```
1000  OPTION BASE 1
1010  INTEGER Spana
1011  INTEGER Ro, Buf, Out, Rognd
1020  !
1060  Spana=2718              ! GPIB Address
1070  Minf=1.00E+8            ! Sweep start frequency
1080  Maxf=900E+8             ! Sweep stop frequency
1090  Rbw=1.E+6               ! Resolution band width
1100  N=101                   ! Number of inverters in the R.O.
1110  Fcr=1.00E+4             ! Frequency counter resolution
1111  !
1112  Vcc=3.3                 ! Drive voltage
1113  Icomp=4.00E-2           ! Current compliance
1114  !
1115  Ro=2                    ! Pin assignment
1116  Buf=4                   !
1117  Rognd=6                 !
1118  Out=8                   !
1120  !
1121  Init_system             ! Initializes Agilent 4072A
1130  Init_spa(Spana)         ! Initializes E4411A
1131  !
1133  Connect(FNPort(1,9),Rognd)            ! Connection
1134  Connect(FNPort(3,1),Out)              !
1135  Connect(FNPort(1,2),Ro,Buf)           !
1136  Force_v(Ro,Vcc,Vcc, Icomp)            ! Drive R.O.
1140  Set_spa(Minf, Maxf ,Rbw)             ! Set up measurement
1150  Measure_spa(Osc_freq,Amp,Delay,N,Fcr) ! Measure osc. frequency
1170  Disable_spa
1180  Disable_port
1190  Connect
1191  !
1200  PRINT "Freq:";Osc_freq;"(Hz), Gate delay:";Delay;"(s)"
1210  END
```

Figure 2. Measurement program example

Further measurements can be performed in order to get better accuracy if a marker frequency counter function is available on the spectrum analyzer. Unlike a frequency counter, a spectrum analyzer will not return an incorrect value by counting a harmonic of the ring oscillator.

Figure 3 shows example frequency measurement results of actual ring oscillators.

The characteristics shown in Figure 3 (A) were measured on the same device as shown in Figure 1. The results of the frequency measurements are nearly identical.

The connection diagram required for this measurement is shown in Figure 4.

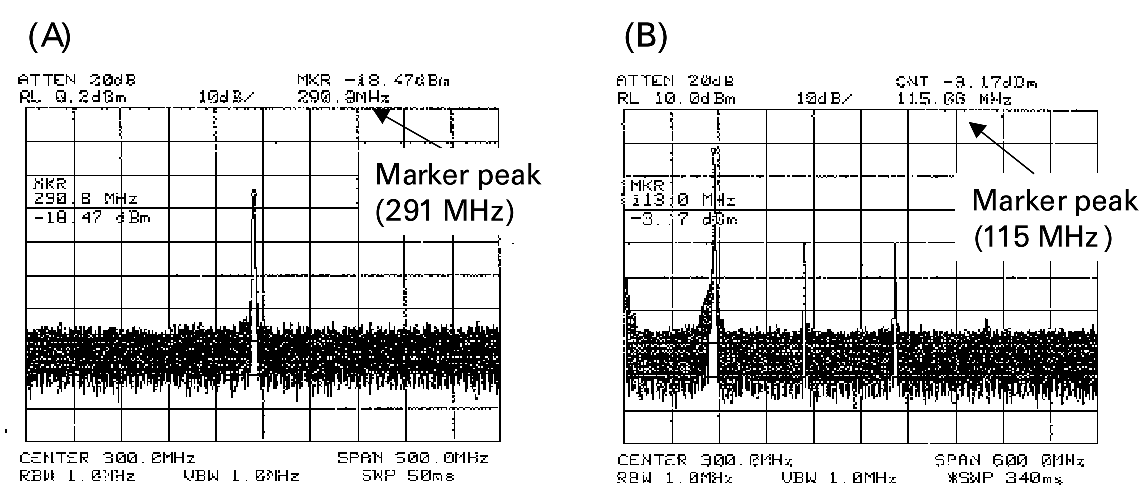

Figure 3. Example of ring oscillator evaluation results at 291 MHz (A) and 115 MHz (B)

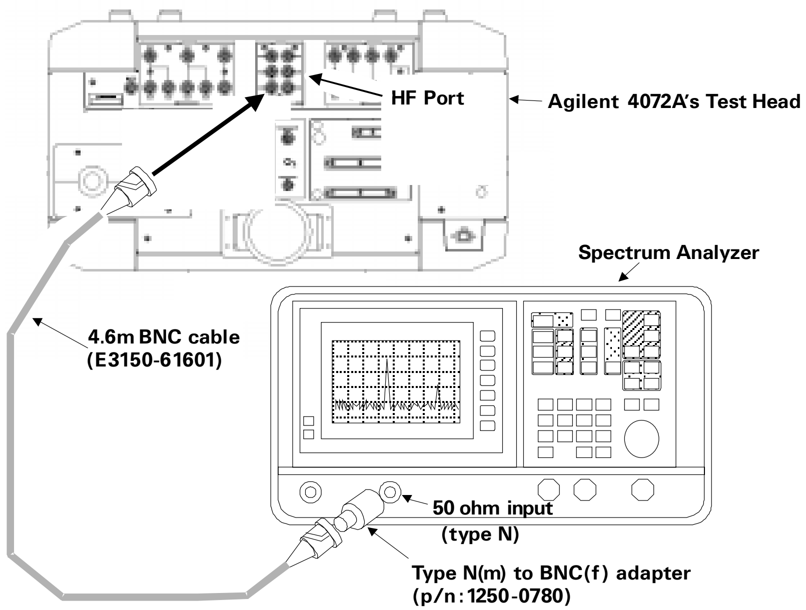

Figure 4. Measurement program example

Conclusion

Gate delay and interconnect delay, both of which are critical parameters in the sub-micron device era, can efficiently be evaluated using the Agilent 4072A Parametric Tester and a spectrum analyzer. Automatic evaluation allows collection of a reasonable amount of data both in R&D during design, and in production for advanced analysis and process monitoring.

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